SSC13-III-10

Pushing the Limits of Cubesat Attitude Control: A Ground Demonstration

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ABSTRACT

A cubesat attitude control system (ACS) was designed at the NASA Marshall Space Flight Center (MSFC) to provide sub-degree pointing capabilities using low cost, COTS attitude sensors, COTS miniature reaction wheels, and a developmental micro-propulsion system. The ACS sensors and actuators were integrated onto a 3D-printed plastic 3U cubesat breadboard (10 cm x 10 cm x 30 cm) with a custom designed instrument board and typical cubesat COTS hardware for the electrical, power, and data handling and processing systems. In addition to the cubesat development, a low-cost air bearing was designed and 3D printed in order to float the cubesat in the test environment. Systems integration and verification were performed at the MSFC Small Projects Rapid Integration & Test Environment laboratory. Using a combination of both the miniature reaction wheels and the micro-propulsion system, the open and closed loop control capabilities of the ACS were tested in the Flight Robotics Laboratory. The testing demonstrated the desired sub-degree pointing capability of the ACS and also revealed the challenges of creating a relevant environment for development testing.

INTRODUCTION

Advancements in small satellite technologies are enabling new classes of missions for ever smaller satellites. Complex missions, that in the past have required larger spacecraft, are becoming feasible, even for cubesats, which until recently have been considered little better than toys or academic instruments. One restriction for cubesats that has limited their range of applicability to date, has been their relatively primitive attitude control capabilities.

To address this problem, a short-term, small scale project was proposed at NASA's Marshall Space Flight Center (MSFC) to be carried out using in-house technology development seed money and a small amount of civil servant labor. The primary objective of the project, which is detailed in this paper, was to design a sub-degree pointing accuracy cubesat attitude control system (ACS), using currently available technology and equipment, and to take the concept of such a system from Technology Readiness Level (TRL) 2 to TRL 4. Without detracting from the emphasis on the primary objectives, the project also had two secondary objectives: to evaluate small, low cost, Commercial-Off-The-Shelf (COTS) hardware designed for small satellites and to integrate low cost hardware onto a cubesat-like breadboard.

The initial plan was to design a 3U cubesat, integrate the subsystems, and then demonstrate the capabilities of the high performing ACS while floating the cubesat on an air bearing in MSFC's high-precision flat floor testing facility. The schedule required these tasks to be completed in six months. As with any project, plans changed and this paper describes the evolution of the design process, results of the attitude control demonstration, and lessons learned throughout the project.

BACKGROUND

This project was initiated by a small team of engineers at NASA MSFC and was funded by the Center Innovation Fund (CIF) through the MSFC Office of the Chief Technologist. The team represented three departments of the MSFC Engineering Directorate and their collaboration involved the following disciplines: Guidance, Navigation and Control (GN&C), Avionics, Flight Software, Propulsion, and Mechanical Design. The MSFC team partnered with Department of Mechanical Engineering at the University of Arkansas who directed the design, manufacturing, and testing of the micro-propulsion system.

The team was able to leverage existing MSFC infrastructure such as the Small Projects Rapid Integration & Test Environment (SPRITE) Lab and the Flight Robotics Laboratory (FRL). The purpose of the SPRITE Lab is to assist in design, development, integration and testing of avionics and software for small, prototype and demonstration projects. The FRL provides a full scale, integrated simulation capability for the support of the design, development, integration, validation, and operation of orbital space vehicles. The facility is centered around a 44 foot by 86 foot precision air bearing "flat floor" which provides a nearly frictionless testing environment.

CONCEPT OF OPERATIONS

A Concept of Operations (ConOps) was developed at the onset of the project to flesh out and clearly define the project scope and to define the design requirements. The ConOps specifies that the cubesat (actually, the cubesat breadboard/mock-up) be integrated onto an air bearing in order to "float" on the flat floor of the FRL. This configuration provides three degrees of freedom; two translational axes in the horizontal plane of the floor and a rotational degree of freedom about the axis normal to the floor. Also, the ConOps makes use of a sun simulator available in the FRL. This allows the cubesat to use a digital sun sensor to supplement its Inertial Measurement Unit (IMU) data for attitude determination.

Commands sent to the cubesat during testing are sent via a wireless modem. The wireless modem also provides the path for real-time telemetry data from the cubesat to be returned to the operators. Through this means, three attitude control modes were specified for testing; a reaction wheel only mode, a micro-propulsion system only mode and a mode where the two systems are combined.

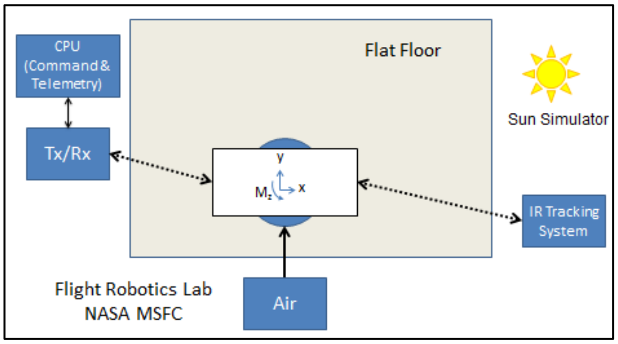

Figure 1 – Concept of Operations

CUBESAT DESIGN

The objectives of the project required the team to design a cubesat-like breadboard containing the majority of subsystems typical of small satellites. The "cubesat" would serve as a platform for the ACS hardware that would perform the attitude determination and control functions. Avionics were also needed to interface with the ACS hardware and flight software would be written to execute the ACS algorithms. A communications system was required to receive user commands and transmit telemetry, and an electrical power system was needed to provide power to all the components. Finally, the cubesat had to be integrated onto an air bearing.

Many opportunities were available to make the cubesat more "flight-like," but the team had to resist these temptations and keep things basic in order to complete the primary objective on a tight schedule and budget. Some of the decisions that were made to maintain simplicity and save time were: use of a COTS Electrical Power System; not considering battery life concerns; providing both 12V and 5V power to the propulsion system and providing external power if needed; use of a COTS communications system; designing the mechanical structure based on testing loads and not the loads associated with the relevant space environment; and exclusion of any thermal analysis.

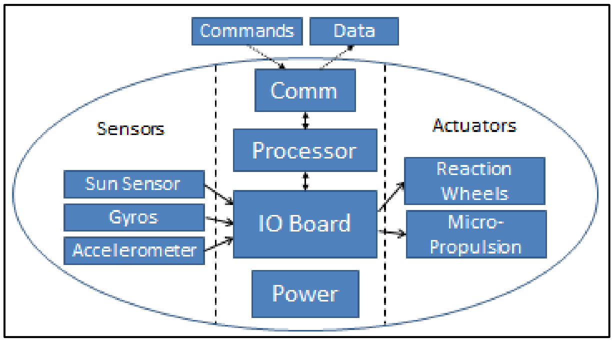

Figure 2 - System Architecture

Propulsion System

The University of Arkansas's Engineered Micro/Nano-Systems Laboratory (EMNSL) was tasked to design, fabricate, and support the integration of the micro-propulsion system. The micro-propulsion system is based on two identical micro-propulsion modules (MPM) mounted at the ends of a 3U cubesat test structure. Each module occupies the volume of 1/2U (nominally 10 cm x 10 cm x 5 cm) and consists of two micro-fabricated nozzles mounted in opposing directions. Each nozzle is operated independently through its respective valves; thus providing 4 independent valve/nozzle combinations for the entire system. In order to provide clockwise/counter-clockwise yaw rotations, the modules activate the opposing thrusters to provide a moment couple.

Although the focus of this project was to provide strong yaw control with micro thrusters in conjunction with onboard momentum wheels for fine control, proper pairing of the nozzles can also provide single axis lateral control perpendicular to the cubesat's long axis or coordinated maneuvers using all four nozzles. The overall design of the MPM with the interface connector is shown in Figure 3. Underneath each face plate with the interface connector is the controller board, which is shown in Figure 4. Also shown is the inside of the propellant tank with the baffle system to minimize propellant sloshing.

Figure 3 - Micro Propulsion System, Connector

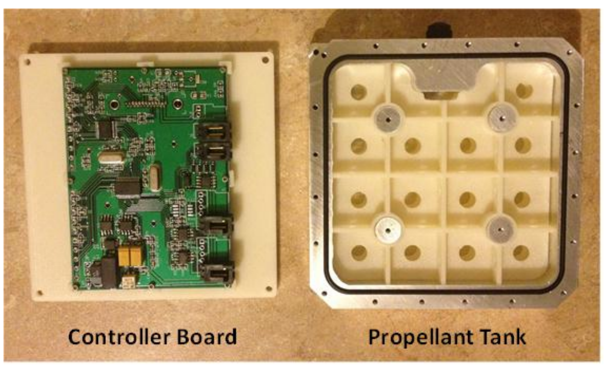

Figure 4 - Controller Board and Propellant Tank

Each propulsion module is fabricated of 6061 aluminum alloy for the propellant tank (1/4U) and Fused-Deposition Modeling (FDM) 3D printed acrylonitrile butadiene styrene (ABS) enclosure (1/4U) for its controlling electronics and interface connectors; this is shown as metallic and white, respectively, in the figure below. At the end of the valves, the silicon micro-fabricated supersonic nozzle is anodically bonded with Pyrex glass covers. The cross section, mounting, and interface of the MPM is designed to be compatible with the Pumpkin™ CubeSat Kit, the components of which form the SPRITE lab's cubesat bus. The controller board for each of the MPMs is designed and fabricated with the *www.expresspcb.com* resources, incorporating 2 Microchip microcontrollers (PIC18F26K22 and PIC18F14K22), voltage step-up (5V input to 12V output), and spike-and-hold valve driver circuitries. The interface is via the 25-pin 2-row Micro-D connectors (male).

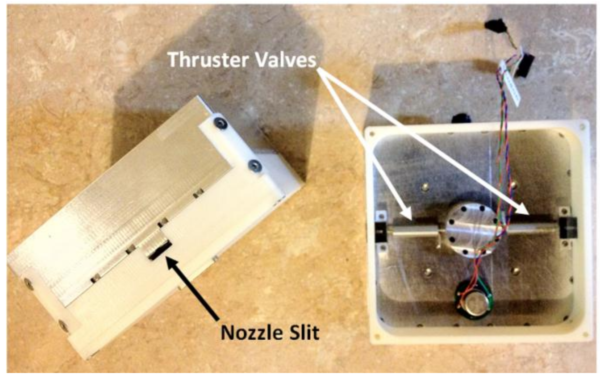

Figure 5 - Micro Propulsion System

A single controller board was delivered to the SPRITE lab by the fourth month of the project and was used to check the communications interface with the cubesat bus. The other MPM was delivered two weeks later. The University of Arkansas team subsequently visited the SPRITE lab two weeks after that to deliver the propellant (HFC-236fa, Dymel® medical grade) and perform on-site check-out of the propulsion modules using the intended propellant. Arkansas continued to provide support for the project and later replaced a broken voltage step-up chip. The time period from the start of the project (material purchase authorization) to delivery of the two MPM units covered less than 6 months.

Mechanical Structure

Development of the mechanical structure began with research on typical cubesat structures and collection of specifications for the components that would go inside the cubesat structure. The sun sensor, reaction wheel assembly, and individual PC cards were then modeled with 3D CAD software using the collected information. After stacking the cards in the proper order and arranging the reaction wheel, it was decided that a bracket was needed to allow the sun sensor to fit inside the design space. The 3U cubesat that was to house all these components was then designed after the sun sensor bracket design was modeled. The cubesat structure was designed to be 0.125 inches thick since it was to be printed out of ABS plastic using a 3D printer.

Two design iterations of the cubesat were printed. The first was for fit check purposes for developing cabling. The second allowed for the attachment of an air bearing and thus had to be made slightly longer for clearance of the air fitting, thus the PC cards and reaction wheel had to be spaced farther apart.

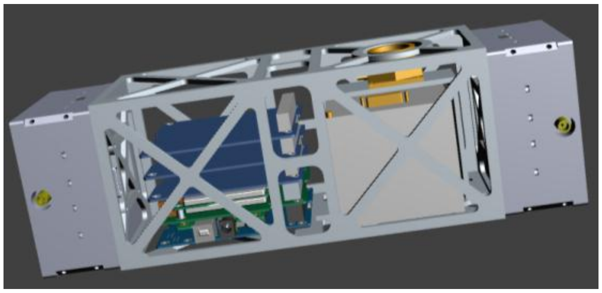

Figure 6 - Cubesat CAD Model

The development of an air bearing was an additional project challenge. Having experienced great success with 3D printing of the cubesat structure, the decision was made to attempt to create an air bearing also using the 3D printer and ABS plastic. Based on previous aluminum air bearings used at MSFC, a 4" diameter design was created. Since the air bearing was being printed, the complex design could be made into one piece thus eliminating the need for seals or fasteners. The plastic air bearing was then successfully tested using a 5 pound mass to simulate the cubesat structure. A NASA New Technology Report (NTR) was generated to capture the effectiveness of the promising new ABS plastic air bearing.

After the designs of both the mechanical cubesat structure and the air bearing were completed, a final mass report, complete with center of gravity and moments of inertia, was calculated for use in the ACS algorithms. This report was used to calibrate the two propulsion boxes mounted on the ends of the cubesat structure.

Instrument Board

The CubeSat instrument board was designed primarily to easily connect the ACS sensors and actuators using short electrical harnesses. The board provides micro-D connectors to connect the thrusters, reaction wheel, and sun sensor. These connectors allow interconnecting electrical harnesses to be easily installed and removed. The IMU is mounted directly to the instrument board via custom mounting holes and a short ribbon cable.

The four remotely mounted instruments require two serial data protocols and must share the single UART channel from the flight computer. This is accomplished with protocol converters and multiplexing circuits. The board thus provides a one to four channel multiplex capability with RS-232 and RS-485 serial protocols available.

Voltages of 3.3V, 5V, and 12V are managed on the instrument board. The 5V main bus provided by the cubesat power supply is regulated down to 3.3V by the board to power the IMU. 12V is generated solely for the reaction wheel using the 5V and a DC-DC converter.

Testing was performed on each functional block of the board, moving progressively to a full system test. The power supplies were dummy loaded to specification and checked for proper value. Second, communication channels were tested using simple loopback methods. Next, individual instruments were integrated with communication and the command protocols were tested. Finally, a full integration test was performed.

Flight Software

The software for the cubesat ACS test article operates at two rates, 1Hz and 10Hz. The driving clock is a 10Hz data ready interrupt from the IMU. This ensures minimal latency between IMU samples and software processing. It also ensures that the IMU and software do not drift due to use of different clocks.

The 10Hz task executes the control system, sampling the IMU and calculating commands to be sent to effectors. It also issues commands to the thrusters.

The 1Hz task handles command and telemetry through the RF communication system, collection of status data from the thrusters and sun sensor, and commanding and status collection from the reaction wheels.

The entry point for the software is the main routine which performs initialization, spawns the 10Hz task (Control_task) and the 1Hz task (Housekeeping_task), and configures the ISR (interrupt service routine) for the IMU, which governs system timing. After completing these tasks, the main routine is finished and its execution completes.

The two threads (10Hz and 1 Hz tasks) continue to run. The execution of each is governed by acquisition of a semaphore that is released at the proper time by the IMU data ready interrupt.

Attitude Control System

A simple ACS was designed to allow for both the open loop and closed loop control of the cubesat. The open loop control allows the user to directly command a wheel speed to the reaction wheels or to command a firing of the propulsion system. The closed loop control uses incoming attitude and attitude rate data from the IMU along with a PD controller (Proportional, Derivative) to calculate a desired torque. Depending on the desired actuator, the desired torque is either passed directly to the reaction wheels or is converted to a thruster command pairing. The simple controller does not use the digital sun sensor or filter any of the incoming IMU data nor does it have the capability to manage the momentum of the reaction wheels.

Before testing on the cubesat, the controller was designed and simulated in MATLAB Simulink. A simulation was developed from a previously developed small satellite ACS simulation and modified to model the dynamics associated with the FRL Flat Floor.

A more complex ACS was designed in addition to the simple ACS, but the complex ACS was not used due to time constraints on the project. The design of the complex ACS resembles one that is more flight-like. It has both the open and closed loop attitude control functions, but it also has a significant number of enhancements that significantly improve performance. The first feature is an attitude determination filter that blends the sun sensor measurements and IMU data to significantly improve attitude knowledge. The attitude knowledge of the simple ACS only allows for knowledge of the attitude relative to the initial cubesat orientation, but the filter provides knowledge with reference to a fixed reference frame and is independent of the initial orientation. The second significant feature of the advanced ACS is the ability to manage the momentum of the reaction wheels using the propulsion system. A third feature is to effectively and safely manage the various operating modes of the ACS. The team planned to test the complex ACS in the summer of 2013.

System Integration & Testing

The system integration for the project was performed in the SPRITE Lab and consisted of a variety of activities. The majority of the activities involved creating and testing the interfaces between the flight software and GN&C hardware via the instrument board. These interfaces are required for the flight software to receive data from the sensors and to send commands to the actuators. Additional activities included interfacing with the transmitter and the electrical power system. All of the interfaces described above consist of both an electrical interface and a software interface. A list of the systems integration tasks are as follows:

- Propulsion System Integration (via breakout board)
- IMU Integration (via breakout board)
- Sun Sensor Integration (via breakout board)
- Reaction Wheels Integration (via breakout board)
- Communications System Integration
- Electrical Power System Integration

While waiting for the availability of the instrument board, interface testing of the IMU and propulsion system was completed using electronic breadboards. A single electronics card for the propulsion system was provided a couple of weeks before final delivery of the two units in order to allow the team to continue with the interface testing. The electronic breadboards were replaced with the instrument board once it completed its own testing and the project continued with the interface testing of the reaction wheels and sun sensor as the hardware arrived.

Figure 7 - Cubesat Assembly with Hardware Before Final Integration

Initial integrated testing immediately showed, as expected, that there was a power problem. The current draw of the system was greater than the limit of the Electrical Power System. The predetermined solution to this was to provide external power to the micro-propulsion system through the avionics board. External power was added to the cubesat and integrated testing continued in the SPRITE Lab.

Preliminary Testing

After the completion of the integrated testing, the cubesat was taken to the FRL Flat Floor to test out the capabilities of the attitude control system. With the cubesat integrated onto the air bearing, the test setup involved using tubing to run air to the air bearing and a power cord to provide the Cubesat with power. A laptop was used to command the Cubesat and to receive telemetry using a communications system.

Initial testing showed that the reaction wheels did not have enough torque capability to overcome the torsional stiffness of the air bearing supply hose and the power cord. The cubesat could be rotated in one direction and then the tubing would cause the cubesat to rotate back to its original starting point. A more detailed analysis of the setup showed that the disturbance torque from the torsional stiffness of the tubing is slightly larger than the maximum torque capabilities of the reaction wheels.

This result led to the realization that both the tubing for the air bearing and the power cord needed to be eliminated. The quick solution for eliminating the tubing was to hang the cubesat from wax line. As for the power cord, the power system was reconfigured with an additional battery, and this proved to be successful. The second battery was configured to power all the sensors and actuators connected to the instrument board and the original battery was used to power only the processor and transmitter. These quick and temporary solutions involving the wax line did not allow demonstration on the flat floor and the team is currently pursuing permanent solutions.

With the modifications complete, the reaction wheels were directly commanded to specific wheel speeds to verify the reaction wheel torque could overcome the torsional stiffness of the wax line. The data from this test was used to characterize the reaction wheel and will be incorporated into the reaction wheel model for future analysis. This testing also verified the ACS open loop control.

ACS TESTING & RESULTS

The removal of the external power cord and hanging of the cubesat allowed the team to perform the ACS testing. Testing began with using reaction wheels only and then proceeded to using the micro-propulsion system only.

The initial testing of the closed loop control using only reaction wheels demonstrated the ACS could dissipate a small attitude rate and hold a desired attitude to about a one degree attitude error. The initial testing used IMU data only, the PD controller, and the reaction wheels to drive the attitude error and attitude rate to zero. The initial conditions of the test were an attitude error of 130°, a -6 deg/sec body rate and all reaction wheel momentum available. The attitude error time history is shown in Figure 8 and the body rate time history is shown Figure 9. The results show the gradual change in wheel speed to damp the attitude rate and then the eventual settling of the attitude error to around one degree.

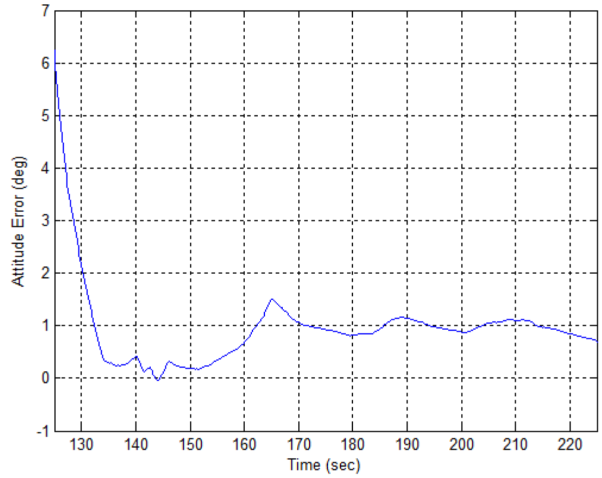

Figure 8 - Attitude Error (RW Only)

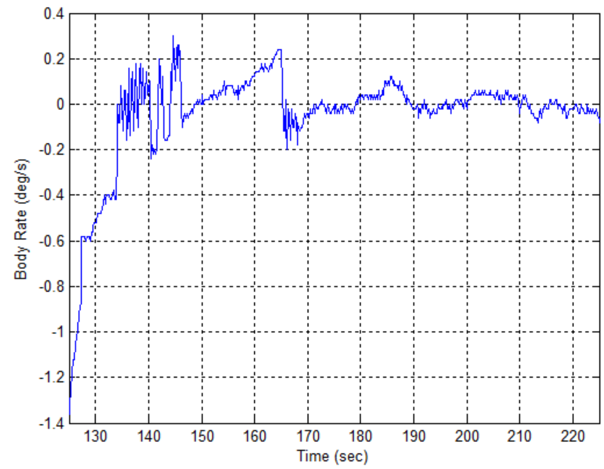

Figure 9 - Body Rates (RW Only)

The subtleties of the reaction wheel dynamics and its effects on the body rates are shown by the time history of the commanded and actual reaction wheel speed in Figure 10. The reaction wheel has a deadband around 0 rpm of +/- 50 rpm where the wheel speed cannot be commanded to a speed between -50 rpm and 50 rpm except for zero. This is visible in the plot of wheel speed and is seen when the measured speed stays at -50, 0, or 50 rpm even though the commanded wheel speed is less within these values. After settling, the attitude error slightly peaks (165 seconds) due to the lack of fine resolution control of the reaction wheel while the wheel speed is in the deadband. A more complex controller could account for this by biasing the wheel speed.

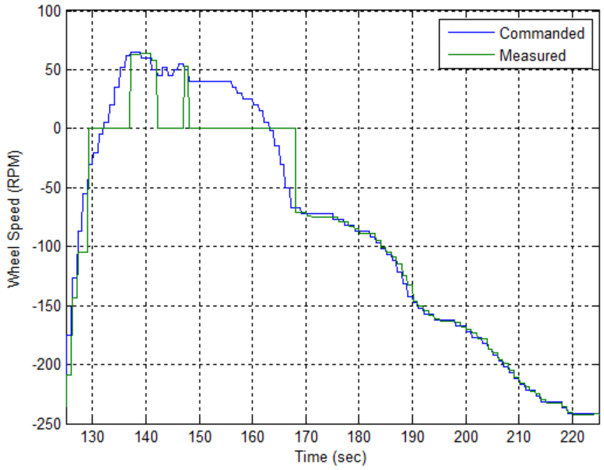

Figure 10 - Reaction Wheel Speed (RW only)

Another characteristic of the test was that the cubesat was not in a completely torque free environment. This is seen by the gradual decrease in wheel speed after the controller has settled at the desired attitude. The reaction wheels will eventually reach the lower limit of the wheel speed and no longer be able to be counter the external torque on the spacecraft. This will lead to the control system not being able to hold the desired attitude.

The testing of the closed loop control path showed the limitations of relying only on reaction wheels and the importance of being able to dissipate reaction wheel momentum using either the propulsion system or magnetic torque rods. There were times during testing when too large of a rate was induced and the reaction wheels became saturated while trying to provide control. Additionally, the torsional stiffness of the wax line eventually led to the saturation of the reaction wheels. The addition of the propulsion system will aid in dumping momentum of the reaction wheels.

LESSONS LEARNED

This project served as a systems training experience for the majority of the team and many valuable lessons were learned throughout the project. Some of the lessons may be obvious to an experienced engineer, but they serve as a good reminder to anybody involved in satellite design. The following are a few of the lessons learned during the project concerning satellite design:

- Don’t underestimate the complexity of designing a spacecraft and the value of all the systems.
- Understand risks and how to eliminate them where possible.
- While COTS components reduce cost, each vendor has its own unique interface. This means that each additional COTS component adds another increment of development and integration time. Standardization in the market could lead to significant savings in development time.
- Plan more time in the schedule for integration and testing.

In addition to the lessons learned during the design process, the team also learned an important lesson relating to testing. The team found that creating a relevant environment for testing can sometimes take as much or more effort than developing the technology which is being tested. Challenges were experienced throughout the project, but the lengthiest delays were due to the difficulties associated with trying to eliminate milliNewton-meter external disturbance torques from the testing environment.

Finally, the team learned that innovation, such as the printed air bearing, arise somewhat serendipitously when you’re trying to solve challenging problems.

FUTURE WORK

At the time of publication deadline, the team is currently implementing a more complex ACS controller. The complex ACS uses the sun sensor in the control loop and will significantly improve the accuracy of the attitude determination. Additional logic has also been added to the control algorithms to make the controller more efficient. The new controller is similar to a phase plane controller and the original PD controller will execute once the attitude error and rates are within a specified region. This eliminates the inefficiency of the PD controller when handling either large attitude or rate errors.

The team is also designing a 6U cubesat to demonstrate proximity operations with a cooperative target spacecraft. The 6U cubesat design is based off the experience gained from the 3U design, but with the addition of a smartphone to act as a proximity operations sensor. The 6U cubesat will be mounted to a self-sufficient air bearing in order to not constrain the translation and rotation of the cubesat. This work is expected to be completed by the end of September 2013.

CONCLUSIONS

A 3U cubesat-like breadboard was designed and integrated by a small team of engineers at NASA MSFC to push the limits of attitude control using small, cost effective hardware. The “cubesat” was designed around the ACS hardware: digital sun sensor, MEMS IMU, miniature reaction wheel, and a cold gas micro-propulsion system developed by the University of Arkansas. A 3D plastic printed air bearing was also developed for the project.

Testing of the ACS showed the potential for achieving sub-degree attitude pointing using current COTS hardware. The cubesat successfully maintained a pointing error of a degree while having to compensate for a significant external disturbance torque and without use of the digital sun sensor. Future ACS work includes implementing an attitude estimation algorithm and a more flight-like controller with momentum management.

Acknowledgments

The author would like to express gratitude to the NASA Marshall Space Flight Center for providing an opportunity to pursue this work. He would also like to express gratitude to the team members involved in the project: Evan Anzalone, Chris Becker, Pedro Capo-Lugo, Daniel Heater, Ricky Howard, Adam Huang, Jose Molina, Steven Peeples, John Rakoczy, Kevin Sykes, and Scott Wenger.